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SOME CIVIL ENGINEERING AND MANAGEMENT ASPECTS OF CONVERSION FROM JP-4 TO JP-8 FUEL BY THE UNITED STATES AIR FORCE IN THE CONTINENTAL UNITED STATES

Steven M. Pittman, 2d Lt, USAF
J. Parke K. Smith, 2d Lt, USAF

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The purpose of this thesis is to examine the possible conversion in the CONUS from JP-4 turbine fuel to JP-8. While many studies have been conducted to analyze the effects of the conversion on aircraft and support systems there has been little work done to analyze the effects on the facilities in which the fuel is stored and transported. This thesis examines the effects of conversion on the fuel bulk storage tanks and on

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the piping and pumping system used to transport the fuel. Where appropriate, recommendations have been made concerning the modifications necessary to these facilities to counter any detrimental effects associated with the conversion.

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SOME CIVIL ENGINEERING AND MANAGEMENT ASPECTS OF CONVERSION FROM JP-4 TO JP-8 FUEL BY THE UNITED STATES AIR FORCE IN THE CONTINENTAL UNITED STATES

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Facilities Management

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Chapter 1

INTRODUCTION

Statement of the Problem

There are virtually no Air Force systems within the continental United States (CONUS) which presently use JP-8 or other kerosene-based fuels. For the purpose of this thesis project, these Air Force systems are defined as storage and transportation facilities. Due to the possibly significant differences between JP-4 and JP-8 fuel, consideration must be given to the possible direct effects of converting these systems to accommodate JP-8. Using JP-8 may bring about a change in the design requirements and adequacy of existing physical facilities. Therefore, this thesis effort will examine key points involving the adequacy of design of the existing facilities from the conversion point of view.

A tremendous amount of research has been done as regards the impact of JP-8 on aircraft and aircraft systems; however, little attention has been given to the effects of JP-8 on the existing physical facilities and equipment listed above. Thus, a need exists to fill this void.

Background

With each succeeding year, the Air Force has found itself faced with the problem of greater competition for the naptha base of JP-4 aircraft turbine fuel. The competition for naptha comes from civilian industry. Naptha is an important ingredient used in the production of synthetic natural gas and low-lead gasoline. Naptha is also under increased demand for its use in petrochemical feedstocks (7:14). As demand for naptha steadily increases from other fields, the availability of JP-4 will decrease since only a certain percentage of crude oil can be refined into naptha and then processed into JP-4.

Realizing the potential problem of JP-4 availability which could arise due to increased competition for its naptha base, the Aeronautical Systems Division of the Air Force determined that an alternate fuel designated JP-8, North Atlantic Treaty Organization (NATO) designation F-34, deserved further consideration (3:2).

Procurement of sufficient quantities of fuel due to fuel shortages and changes in the fuel supply structure may become difficult in the future. In 1974, the United States Air Force Scientific Advisory Board recommended an alternative for dealing with this problem. Their recommendation was for the Air Force to convert from JP-4 to JP-8. This conversion would tend to reduce competition coming from petrochemical feedstocks and low-lead gasoline. However,

there is no valid information available indicating that the conversion to JP-8 will help reduce the long term fuel shortage problem. Due to the complexity of fuel pricing and availability in general, it may be premature to assume that conversion to JP-8 will help in the fuel supply and price situation. On the other hand, the Board decided that, in the long run, a switch to JP-8 will produce a net beneficial effect (11:2).

Because JP-8 is a kerosene-based turbine fuel, there is an insignificant requirement for naptha in its production (16:1). Chemcially, JP-8 closely resembles the kerosene-based commercial jet fuels Jet A and Jet A-1 (11:2). In fact, JP-8 would be exactly like Jet A-1 if it did not contain the icing and corrosion inhibitors which are required by Air Force standards (23). A majority of the aircraft operated by the United States Air Force are authorized to be flown on Jet A and Jet A-1, commercial turbine fuels whose burning characteristics are similar to JP-8. Operating characteristics and procedures are therefore available or can be set forth from previously obtained data for many of these aircraft (11:2). Incidentally, it should be mentioned here that Jet A is the predominate fuel used by commercial airlines in the United States. Jet A-1 is the predominate fuel manufactured and utilized throughout Europe and other areas such as Indonesia (23).

The switch to JP-8 would place the Air Force in direct competition with the commercial air carriers. This competition and the fact that less crude can be converted into JP-8 than JP-4, does present a formidable argument against total or partial conversion to JP-8. However, the fact that total potential for production of JP-8 in this country has not been reached must be considered. At the present time, kerosene-based fuel production in this country is centered around the Gulf Coast and far western regions. Should conversion to JP-8 become reality, there is no doubt that production could substantially increase as larger refineries throughout the country begin to produce JP-8. The smaller refineries which now produce the majority of JP-4 for the Armed Forces would suffer initial financial setbacks during a conversion of their facilities from JP-4 production to JP-8 production (23). It is felt, however, that the financial burden can be cushioned by the issuance of subsidies by the Government for conversion construction.

In general, it is believed that the availability and cost advantages of JP-4 are fast disappearing and being replaced by the advantages of using JP-8. Also, use of JP-8 by the Air Force would bring it in line with other NATO countries already using this type fuel. Thus, conversion to JP-8 would represent a "major step toward the realization of worldwide fuel standardization with its attendant logistic capability and overall costs savings advantages [8:3-4]."

Scope of the Problem

A CONUS conversion by the Air Force to JP-8 will directly or indirectly affect a great number of facilities and equipment within the Air Force. Everything from the largest aircraft using the new fuel, down to the smallest pipe transporting it will be touched by the conversion in some way. This is not to say that JP-8 will have a great negative effect on all fuel related systems, but neither does it suggest that the effect will be totally beneficial. A great deal of study is required concerning each facility, system, and piece of equipment before JP-8 can be introduced into the present JP-4 environment. Therefore, consideration of the items which will be affected should include both beneficial and harmful effects of using the new fuel.

Study of the possible conversion would center around a variety of subject areas. For example, the future availability of JP-8 is of great concern. Also, the cost of conversion, whether material or in man-hours, is an area which needs further research. The list could continue into many other regions.

In an attempt to narrow the research effort, this thesis team will look at some of the facilities and equipment which JP-8 will directly affect. Of course, even this narrower view of the total conversion problem is rather broad; thus, further refining of the situation is required.

The impact of JP-8 on Air Force Civil Engineering will be the general topic of concern.

Again, the research needs further defining. Air Force Civil Engineering (AFCE) is a very large organization actively involved in the operation and maintenance of Air Force bases. Because of this size and complexity, the authors feel that the facilities and equipment at any two bases involving AFCE organizations are not necessarily the same. Therefore, this thesis effort will take a general approach when looking at the conversion prospect as it applies to AFCE so that, with modifications unique for each base, this research can be used by Civil Engineering Squadrons at all CONUS bases where JP-8 will be used.

A further breakdown of the research occurs at base level in Civil Engineering. Since JP-8 is a jet fuel, only those areas in which the facilities and equipment will be directly affected by this type of fuel will be considered. Generally, this will involve the Civil Engineering Liquid Fuels Unit.

The Liquid Fuels Unit is concerned with many items regarding the storage and transfer of jet fuel. This concern ranges from the storage tanks themselves to the pipelines on base which deliver the fuel. The maintenance and upkeep of these facilities and related equipment is the responsibility of Civil Engineering.

The final breakdown or defining of the research involves the facilities and equipment within the Liquid Fuels Unit. Due to limited time, it would be impossible to consider every item within this Unit which will be impacted by a JP-8 conversion. Therefore, only the major items of interest will be considered. These are, first, the aboveground bulk storage tanks and second, the pipes and pumps which carry the fuel from the storage tank to the truck refueling area. Consideration will not be extended beyond the point of the truck refueling area since the trucks themselves are not controlled or maintained by AFCE.

Fuel Qualities

There are several significant differences between the properties of JP-4 and JP-8 turbine fuel. These differences are largely due to the difference in composition. Conventional JP-4 consists of approximately seventy percent naptha and thirty percent kerosene (2:3) whereas JP-8 is made up of nearly one hundred percent kerosene (23).

One of the most important differences between JP-4 and JP-8 is the flash point: 100°F for JP-8 and less than (-)20°F for JP-4 (13:6). This means that JP-8 does not reach its flash point until the fuel is heated to 100°F and above--a hot day in a moderate climate. On the other hand, JP-4 reaches its flash point at a low temperature meaning that the potential for an explosion exists even on very cold days in a moderate climate.

Another very important difference is the vapor pressure of the two fuels. Vapor pressure is normally expressed in pounds per square inch (psi) at 100°F. The vapor pressure of JP-4 is approximately 2 to 3 psi at 100°F (4:5) making it a fairly volatile fuel. JP-8 has a vapor pressure less than 0.10 psi at 100°F (4:7) making it substantially less volatile than JP-4.

A fuel property which becomes very important at high altitudes and in cold climates is the freezing point. JP-4 freezes at approximately (-)72°F whereas JP-8 freezes at about (-)58°F (13:6). Both pilots and ground crews must be aware of this potential problem in order to avoid the risk of having a fuel line restriction caused by frozen fuel.

One aspect of JP-8 that has the potential of causing structural damage and aircraft weight and balance problems is its specific gravity which is 0.816 ± 0.030 (13:6). This is a considerable increase over the specific gravity of JP-4 which is 0.776 ± 0.028 (13:6). In essence, JP-8 is a heavier fuel.

Flow problems may be encountered due to the increased viscosity (measured in centistokes) of JP-8. For example, at (-)30°F the viscosity of JP-4 is rated at 3.6 centistokes while that of JP-8 is 15 centistokes (13:6). This is a significant difference which could hinder engine performance due to insufficient fuel flow.

One very important property of jet turbine fuel is heat of combustion as measured in Btu's per pound of fuel. Roughly speaking, this is the amount of energy which is obtained from the fuel upon combustion. Both JP-4 and JP-8 have a heat of combustion of 18,400 Btu's per pound indicating that there is no energy compromise between the two fuels (4:10). In fact, since a pound of JP-8 is actually less volume than a pound of JP-4 because of its higher specific gravity, it is possible to obtain more Btu's for the same volume (1). It must be remembered, however, that additional poundage or Btu content is limited by weight and balance characteristics of the aircraft. For a listing of the above figures, refer to Table 1.

Table 1

Fuel Properties**

ITEM	JP-4	JP-8
Components	70% naptha, 30% kero.	100% kerosene*
Freezing Point	(-)72°F	(-)58°F
Flash Point	(-)20°F	100°F
Boiling Range	140° - 460°F	320° - 525°F
Vapor Pressure	2-3 psi at 100°F	0.10 at 100°F
Heat of Combustion	18.400 Btu/lb.	18,400 Btu/lb.
Specific Gravity	0.776 ± 0.025	0.816 ± 0.030
Density (at 60°F)	1.453 - 1.553 slugs/ft^3	1.502 - 1.625 slugs/ft^3

* There is some naptha content in JP-8, but this content is insignificant as compared to JP-4.

** Data for this table can be found in source numbers 13 and 23.

Literature Review

In a memorandum prepared for then Deputy Secretary of Defense Ellsworth, it was noted that conversion to JP-8 would have a significant impact on USAF operations and logistics. Various problems with conversion were listed and it was noted that it would cost the Air Force a good deal of money to make modifications to aircraft and other equipment (17:2-5).

The Air Staff has not yet taken a position regarding the use of JP-8 in the CONUS; however, because of the difficulties and uncertainties associated with the petroleum market, Air Force aircraft should be capable of using more than one fuel type as suggested by the USAF Scientific Advisory Board study (2).

The Defense Fuels Supply Center feels that industry would not be able to meet peacetime demands for JP-8, much less wartime demands. It states that mandatory allocation would probably be necessary in order to meet Air Force requirements for JP-8 (16:2).

In a study prepared on the impact of fuel properties on jet fuel availability by Bonner and Moore, it was noted that jet fuel specification relaxation would have a definite effect on availability. The more the standards are relaxed, the easier it is to obtain more of the fuel desired, in this case, JP-8 (8:1-4). In general, industry would like to see the Air Force relax its standards as much as possible.

For an example, industry would like to see the freeze point raised. This would be unacceptable to the Air Force, however, since this would limit mission altitude capability. It must be remembered that the relaxation of specifications would improve availability but this improvement would vary and the problems associated with relaxation are many (23).

Because of the amount of success the Air Force experienced during the United Kingdom portion (Phase I) of the NATO conversion to JP-8, the Air Force has realized that conversion is not as much of a problem as was anticipated only a year ago. That is, no insurmountable problems have been encountered with aircraft and related equipment. Also, it is expected that industry can react to a CONUS conversion provided "sufficient time and legislation exists to allow them to expand gradually before we begin any conversion beyond NATO." Industry may have already been provided with a hint of things to come because of the recent United Kingdom conversion. Experts indicate that it will take from three to five years of preparation before industry will be able to produce the amount of JP-8 which would be required by the Air Force in the event of a total conversion (2). The three to five year interval mentioned above is considered the normal production facilities and logistics lead time. It must be kept in mind that JP-8 availability problems have already been encountered by United States

commercial carriers. The addition of Air Force requirements for JP-8 may substantially increase this lead time (23).

The minutes of the JP-4 to JP-8 fuel conversion conference of March, 1978, gives an overview of the various problems considered. Several speakers briefed on mainly the technical aspects of converting aircraft and engines. The fuel conversion schedule for the United Kingdom was presented (9:1,2).

A technical report on fuel standardization of aviation turbine fuels by the Joint Technical Group on Fossil Fuels concluded that Navy aircraft presently using JP-5 and JP-4 could convert to JP-8 with no modifications and also that most Army aircraft could convert with no problems. It stated that more testing is needed before the impact of conversion on the Air Force could be estimated. The report noted that military departments should begin to phase-in the use of JP-8 in land-based aircraft which can use the fuel (7:13-16).

Recently, it has been noted that the Army is having substantial problems in converting its helicopters to JP-8. The helicopters are having a serious cold weather start problem. It is difficult to say at present whether the Army will be able to convert its helicopters to JP-8 use (23).

In a briefing prepared by Colonel Charlie B. Moore, several advantages and disadvantages associated with

conversion from JP-4 to JP-8 were noted. Problems with cold starts and aerial relights were noted as well as the fact that JP-8 is safer than JP-4. He also brought out some of the advantages and disadvantages of converting in the CONUS (13:1-27).

The Air Force Aero Propulsion Laboratory study on the assessment of JP-8 as a replacement fuel for JP-4 concluded that JP-8 offers a definite advantage over JP-4 as far as fuel safety is concerned. The low volatility of JP-8 is the principal reason for its safer characteristics. Also, conversion to JP-8 would virtually eliminate the raw hydrocarbon vapor emission problem evident with JP-4 (4:3).

The future may find the U.S. more dependent on crude oil which has been, up to this period of time, difficult and uneconomical to obtain. It is anticipated that this crude is of the heavy type from which it is much easier to produce JP-8 rather than JP-4 (23). The important point to remember here is that it may be less expensive to produce JP-8 in the future than JP-4 since JP-8 can be produced more economically from heavy crude than can JP-4.

In a 1978 report concerning the converting of USAF aero equipment to JP-8, it was felt that conversion is good but further testing of equipment needs to be done. The report states that the conversion will help standardize fuel use within NATO (12:15,16).

In August of 1968, the Deputy of Fuels Testing of the Aeronautical Systems Division began a study of the low volatility of JP-8 fuel. The study examined relight characteristics of several aircraft while using JP-8. It was found that the characteristics of JP-8 were significantly different from JP-4 and recommended that further study be done on ground support equipment and other equipment related to fuel systems (3:3).

A joint messageform from Aeronautical Systems Division listed some test expenditures associated with engine and aircraft testing. The report stated that the use of JP-8 would help standardize fuel usage throughout the world (1:1-10). The conversion by the Air Force and Army to JP-8 would bring about a more standardized system throughout the world (4:3).

The explosion of a fuel tank led to the complete destruction of a C-5A while it was at Lockheed Aircraft Corporation for maintenance in 1970. After the accident, Lockheed was given permission to switch from JP-4 to JP-5, a Navy fuel similar to JP-8. The accident investigation team concluded that the aircraft, valued at over one hundred million dollars, would not have been destroyed if either JP-5, JP-8, Jet A, or Jet A-1 had been used in lieu of JP-4 (4:7).

It is hoped by the authors that this section of the thesis has successfully convinced the reader of the

possibility of a conversion from JP-4 to JP-8. Such a conversion is definitely possible despite the initial hardships which might be incurred by both the armed forces and industry. In light of this possibility of conversion, then, however large or small, the armed services, in particular the Air Force, must be able to deal with the conversion implementation. Perhaps the most basic element involved in the conversion, after procurement of the new fuel has been realized, is the storage of the fuel. In addition, the fuel must be transported to and from the storage facility. Air Force Civil Engineering is involved with both of these elements to varying degrees. As stated earlier, this thesis will explore topics involving both of these areas.

Research Objectives

The objectives of this thesis are to examine various civil engineering aspects of the possible conversion from JP-4 to JP-8 in the USAF by analyzing possible effects in the physical facilities used to store and transport the turbine fuel. The possible effects to be analyzed will generally be caused by the increased density of JP-8 fuel. Several particular objectives will be addressed. They include, but are not limited to:

1. Determining the structural adequacy of the present fuel storage tanks as associated with possible pressure problems.

2. Determining the structural adequacy of the fuel storage tank foundations as associated with the increased load.

3. Determining the adequacy of the current fuel pumping system as associated with flow and load problems.

4. Determining pipe adequacy as associated with possible flow problems.

Research Questions

1. Will engineering changes in some physical facilities be required in order to facilitate storage and transportation of JP-8 fuel in the event of a conversion from JP-4?

2. Should modification of facilities be required, what will be the lead time associated with the acquisition of materials or equipment required for modification?

Chapter 2

METHODOLOGY

Data Collection Plan

Storage. The major component of a jet fuel storage system is the storage tank itself. In regard to the analysis which must be done, there are two major areas to be considered. These areas are, first, hydrostatic pressure and second, tank foundation considerations.

The adequacy of a fuel tank in resisting hydrostatic pressure is of great concern. Several pieces of information will be needed to perform this analysis. This information will include such items as tank plate thickness and other pertinent design data which can all be found in the American Petroleum Institute's manual 650 (22). Other data needed in order to investigate hydrostatic effects is that which involves the fuel itself. Mainly, the weight of the fuel will be critical because, the heavier the fuel, the more hydrostatic pressure it will generate. Data as to the characteristics or qualities of the fuel can be found in various documents provided by the Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio.

The second area to be considered is that involving the foundation under the storage tank. There must be an

adequate foundation beneath the storage tanks so that excessive settling or shear failure (see Appendix A) will not occur. Mainly of concern here is the load which the tank structure and fuel within it will place on the soil and also the type of soil beneath the structure. The weight of the storage tank, a figure which must be calculated, and weight of fuel must be known. The weight of the storage tank can be calculated using data concerning the type of material of which the tank is made and the amount of this material that is used in the structure. The weight of the fuel can be found as stated in the previous paragraph. As far as data on the type of soil is concerned, this data will be obtained from sources in the field if possible, and if not possible, this data will be obtained from referenced texts on soil mechanics. The data concerning soil type will be of a general nature since the soil beneath any two storage tanks is most probably different.

Transportation. There are two major points which must be addressed in this section: the fuel pumps and the pipe system. Each will now be discussed.

For any pipe system, probably the most important element to analyze is the frictional head loss incurred as a result of the fluid flowing through the pipe. This head loss depends on a number of factors including the fluid flow rate, the roughness of the interior of the pipe, the

cross-sectional area of the pipe, and the viscosity of the fluid. The frictional head loss is important in this research effort because if JP-8 should cause a significant increase in head loss, it would indicate the possible need for modifications in the piping system in order to either accommodate the increased head loss or to decrease the head loss to an acceptable level.

For dealing with the fuel pump system, the important factor to consider is the difference in the energy required to be added to the fluid flow by the pump system in order to maintain any minimum required flows. If a significantly greater amount of energy is required to be produced by the pumps in order to compensate for the physical properties of JP-8 as opposed to JP-4, modification of, or the replacement of, the pumping system may become necessary to overcome possible energy deficiencies caused by the physical properties of JP-8.

Design to Answer the Research Question

Generally, the data collected by the thesis team will be analyzed and, where appropriate, compared to calculated and/or published data. This information will be presented by the authors to show what effects the characteristics associated with the use of JP-8 will have on various facilities and equipment to be considered in this study.

Storage. Two basic areas of concern will be investigated when considering storage tanks. These two areas involve hydrostatic pressure associated with the fuel, and foundation considerations which result from the load which the fuel and tank structure exert on the soil.

Basically, when looking at the area of hydrostatic pressure, this research team will calculate the degree of this pressure which can be developed by JP-8 in a typical storage tank. The required tank shell thickness at various depths in the tank will be calculated using equations given in the American Petroleum Institute's manual 650. These values will be compared against the actual dimensions of the tanks located at Wright-Patterson AFB in order to check the structural integrity of the tanks. If the tank cannot meet the requirements for shell plate thickness, then the use of JP-8 in the tank may cause rupture or other damage to the structure. One must keep in mind that, on the average, JP-8 is heavier than JP-4 which is presently in use. Due to this fact, a "worst case" approach will be used in all equations when referring to the weight of JP-8 since the "best case" situation places the weight of JP-8 within the average weight range of JP-4 (refer to Table 1--Density).

In foundation analysis this research team will be mainly concerned with the matter of whether the existing soil structure beneath a storage tank is capable of withstanding

the additional load produced by JP-8. This thesis team will approach this subject using the critical depth (see Appendix A) as a determinant of foundation capability.

Critical depth will depend on the weight of the structure and fuel. A "worst case" approach will be used in this analysis. Basic equations will be used to determine an increase in critical depth if any, which may occur.

The critical depth is possibly the greatest concern of all when considering the foundation of a storage tank. An increase in weight will cause this depth to extend further downward. Basic equations will be used to determine how far this downward movement will extend. An extension of the critical depth is only a problem when this extension reaches unsuitable soil material which makes for an inappropriate foundation. If unsuitable material is reached, there exists the possibility of either excessive settlement or shear failure or both in the subsurface soil material (10).

Transportation. In dealing with the data obtained for the transportation section of this study, several comparisons will be made. Pump design data will be compared to published data or data calculated by the authors to simulate conditions associated with pumping JP-8. The specific weights of both JP-4 and JP-8 will be calculated. Since operational data for pumping JP-4 is known, a study of the difference between the two specific weights may indicate that use of

JP-8 will cause an overload of the pump's ability. Studying the viscosities of the two fuels in a similar manner may reveal problems associated with reduced flow in the pumping system. Analysis of these two characteristics under hypothetically cold conditions will also be performed in order to determine if any cold weather pumping problems might occur. In general, this will determine whether or not the present pumping system is adequate for JP-8.

Essentially, the viscosity analysis of the pumping system mentioned above will be extended to include analysis of the present piping system. In other words, the viscosities of both JP-4 and JP-8 will be analyzed to determine if flow problems may be encountered due to the increased density and viscosity of JP-8. Both warm and cold weather conditions will be mathematically simulated in order to determine if any existing flow requirements are not met.

Assumptions

As in practically any research effort, some assumptions must be made from the start in order to facilitate the entire research process. This thesis project is no exception. The biggest assumption made was that, eventually, the USAF would convert all of its facilities from the use of JP-4 to the use of JP-8.. Many studies have been conducted, as discussed in the Literature Review, which indicate that

such a total conversion from JP-4 to JP-8 would prove to be a viable and economic alternative to the dwindling potential supply of JP-4.

While no final decision has yet been made concerning the particular fuel that the USAF will eventually convert to, major emphasis has been placed on the kerosene-based turbine fuels such as Jet A, Jet A-1, JP-5, and JP-8. The kerosene-based fuel receiving the most attention is JP-8 so the authors have assumed that the final technical analysis will cause JP-8 to be chosen as a replacement for JP-4.

In accordance with assuming that the conversion will occur, it was natural for the authors to assume that some problems might be encountered when converting the existing storage and transportation facilities from JP-4 to the more dense JP-8. It was also assumed that the most important of these problems regarding storage and transportation of the fuel could be brought out and aired by the authors so that appropriate actions, if required, could be taken by those organizations responsible, mainly the Air Force Civil Engineering Squadrons.

Perhaps the most far reaching assumption that must be made is that present facilities now handling JP-4 are adequate for this fuel to the point that they at least meet, or possibly exceed, design factors including specified safety factors.

There are many bases operated by the USAF--each of them unique. Of those bases which maintain facilities for the storage and transportation of turbine fuel, no two are exactly alike. Therefore, the authors have assumed that generalities can be made about most of the various types of bases. In other words, it was assumed that most of the bases which handle turbine fuels have above-ground storage facilities and have piping facilities all of a similar nature. The research for this thesis project could easily require more time than is available. Therefore, the previous assumption narrowed the scope of this study considerably, allowing this thesis team to examine the facilities at Wright-Patterson AFB and from this examination, to make generalizations so that the results of this thesis effort, with modifications, can be applied to most of the operational bases within the CONUS.

Limitations

The following limitations are imposed due to time restrictions placed on the researchers.

1. The results of this research can be used by Civil Engineering Squadrons only when considering facilities and equipment within the CONUS.

2. This research is limited to the accuracy of the information which is gathered and analyzed.

3. This research applies only to CONUS bases which will utilize JP-8 as a major fuel source and which possess facilities and equipment of a nature similar to that which will be discussed in this thesis project.

4. JP-8 is not currently being used by the military on a large scale basis within the CONUS; therefore, a lack of practical experience involving its use in CONUS military facilities exists.

Chapter 3

ANALYSIS

This chapter begins the analysis portion of the thesis. Here the authors will attempt to answer the research questions which were posed in Chapter 1. Each item previously designated for study will be addressed in this chapter on an individual basis. That is, there will be separate sections for the analysis of storage tanks and transportation or piping systems. The authors feel that the analysis of each item listed above can best be performed in such a manner. The first system or item to be addressed will be the above ground, bulk storage tanks followed by an analysis of the piping system. In both cases, the systems used for examples will be derived from existing facilities located at Wright-Patterson AFB, Ohio.

Storage

The first fact that must be realized before proceeding with this portion of the analysis is that the particular tanks to be discussed herein were constructed to conform to the American Petroleum Institute's manual 650 (5). This standard has been accepted by the American National Standards Institute (22:iii). Therefore, pertinent design data and equations can be extracted from this manual for use in

equations and for comparison of values. It must also be realized that the tank used as an example in this section has exactly the same characteristics as tank numbers 249 through 258 and tank number 236 which are located in the bulk storage tank farm on Area "C" of Wright-Patterson AFB, Ohio. These tanks have an inside diameter of forty-two feet and a height of forty-two feet. They are constructed of seventy-two inch, butt welded courses (see Appendix A) and have a stated capacity of 10,000 barrels of liquid (5; 22:A-2). Ten thousand barrels is equivalent to 420,000 U.S. gallons based on a figure of forty-two gallons per barrel (22:A-2). In practice, the tanks have an absolute maximum capacity of 428,500 gallons which is equivalent to forty-one feet, eleven inches of fuel in the tank. As a matter of practice, however, the tanks are never filled above forty feet due to floating roof restrictions (6). This forty feet of height is equivalent to 409,046 gallons of fuel in the tank. Since the fuel level in the tank is not to exceed forty feet at any time, this thesis team will regard the tank height to be equal to the maximum level of fuel permissible, forty feet. This is logical since all equations to be used in this chapter relate to the fuel level rather than the physical tank height.

As mentioned in the previous chapter, this thesis team will concern itself with only two areas regarding bulk storage facilities. The first area to be analyzed in this

section is the JP-8 and JP-4 hydrostatic pressure exerted on the outer wall of the storage tank. The second topic of discussion will concern an analysis of the adequacy of the foundation beneath a storage tank should JP-8 be used rather than the present JP-4. The reader should keep in mind that although this study uses a tank at Wright-Patterson AFB as its example, the equations and methods to be used are basic and can be applied to any situation in which similar conditions exist.

Hydrostatic effect. The thickness of the shell of the storage tank increases as its position relative to the depth of the tank increases. That is, as the pressure from the fluid inside the tank increases, the tank shell must increase in thickness so that it will be capable of withstanding the additional pressure. As will be proven presently, more pressure is exerted by the fluid towards the bottom of the tank; therefore, the plates at the bottom must be thicker than those at the top. Diagram 1 illustrates this by showing a side view of the tank used as an example in this section.

The analysis that follows will be presented in a logical step-by-step method. The first calculation of importance is that concerning specific weight. This value is found for both JP-4 and JP-8 by multiplying the density

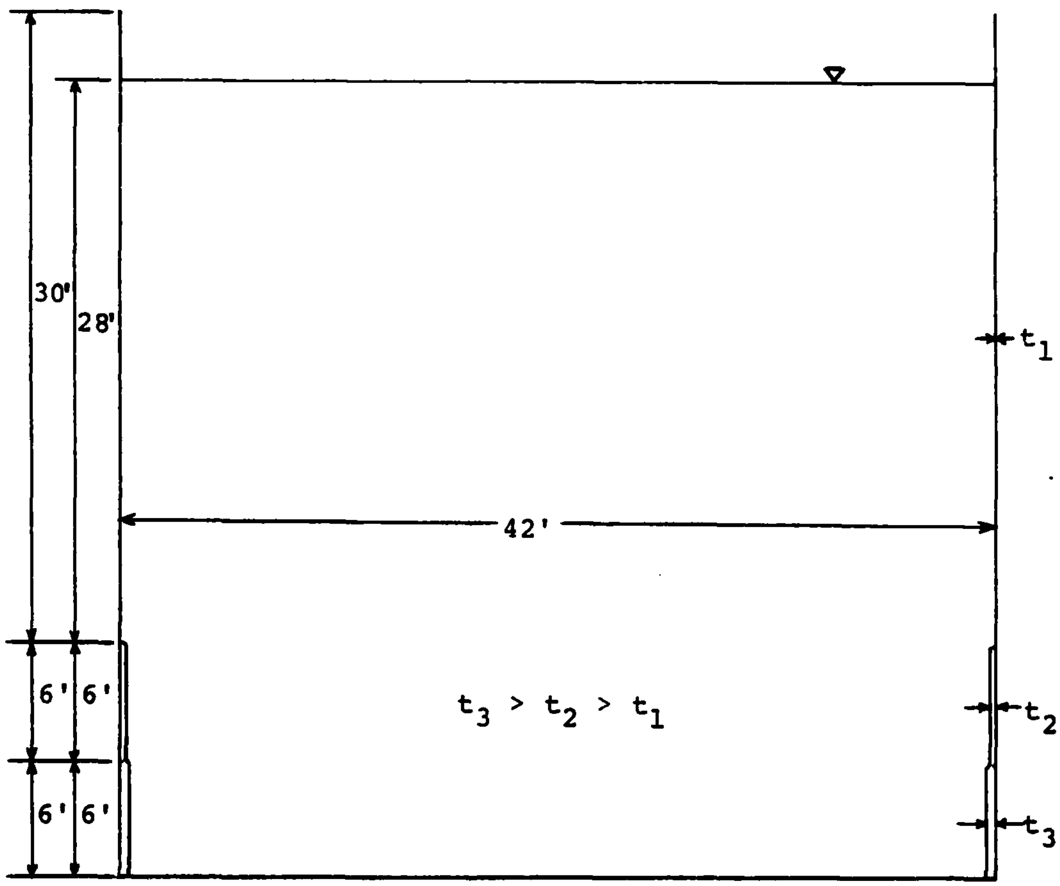


Diagram 1

Fuel Bulk Storage Tank
(not to scale)

value for each fluid by the universal constant for the acceleration of gravity (21:9).

$$\gamma = \text{Specific Weight} = \text{density} \times 32.174$$

Table 2

Specific Weights (60°F) (lbs/cu ft)

Fuel	Specific Weight	
	Lightest	Heaviest
JP-4	46.75	49.97
JP-8	48.33	52.28

As can be seen from the above calculations, JP-8, on the average, is a heavier fuel than JP-4. The lightest values calculated above were found using the lowest values for density found in Table 1. The heaviest values were found using the highest values for density of the two fuels found in the same table.

It must be mentioned here that the values for density vary over a range for both fuels for at least three reasons. First, the grade of crude oil received at the refinery, whether heavy or light, has an effect on the density. Second, the refining process itself, including quality control, can have an effect on the density. Third, the temperature of the fuel itself has an effect on the density (23).

Now that the specific weight has been calculated for both fuels, it is possible to calculate the pressure

exerted by the fuel at various depths in the tank. Rather than entering into a detailed analysis of structural integrity involving strength of materials, this thesis team will use a simple comparison involving an API equation and the actual tank shell dimensions. First, however, some background must be given.

The pressure exerted by the fuel at any depth in the tank can be calculated by multiplying the specific weight of each fuel by the depth at which one wishes to discover the pressure (21:41).

$$\text{Pressure} = \text{Specific Weight} \times \text{Depth}$$

As is obvious when viewing this equation, the greater the depth of the fuel, the greater will be the pressure.

The question to be asked at this point is, At which depths is it imperative to know the pressure exerted by the fuel? This question has a rather simple answer. The points at which the pressure will be most critical are located at the bottom of each plate thickness range. Henceforth, these points will be known as critical points. The importance of the critical points will be explained presently.

As can be seen from Diagram 1, the thickness of the storage tank courses does not increase at a constant rate; rather, the thickness changes occur in two abrupt increases as one moves from the top to the bottom of the tank. As stated above, the pressure within the tank increases with

depth. Therefore, it can be concluded that a course or a series of courses of the same thickness will have to withstand more pressure at the bottom of its length than at its top. For example, the 3/16 inch upper five plates are more likely to rupture at their deepest extension (a fuel depth of twenty-eight feet) due to increased pressure than they are at the top of the tank when the pressure exerted by the fuel is at its lowest value. The same can be said for each of the other two courses of different thickness. A listing of the thicknesses of the example storage tank can be seen below:

Table 3*

Tank Shell Thicknesses

Course	Thickness (inches)
Bottom or first	.241
Second	.206
Upper five	3/16

*Figures provided by CBI (5).

In answer to the question posed in the previous paragraph, the critical points will be located at fuel depths of twenty-eight, thirty-four, and forty feet when the tank is filled to the maximum allowable fuel level of forty feet.

Perhaps at this point, the actual pressure exerted by the fuel at the critical depths should be listed.

Table 4

Fuel Pressure (60°F)

Fuel Depth (ft)	Pressure (PSF) JP-4 Lowest	JP-4 Highest	JP-8 Lowest	JP-8 Highest
28	1309.0	1399.2	1353.2	1463.8
34	1589.5	1698.9	1543.2	1777.5
40	1870.0	1998.8	1933.2	2091.2

The lowest pressure values above were calculated using the lightest specific weights of each fuel while the highest values were found using the heaviest specific weight values. The values listed at the forty foot depth will be most helpful in foundation calculations.

The basic point which the reader should retain from this background section is that pressure increases with depth. Thus, the tank shell must increase in thickness, as one moves from the top to the bottom of the tank, so that the additional pressure can be withstood by the tank structure. It has been mentioned previously that the tank shell dimensions change in two abrupt increases. This is done for both practical and economic reasons which are beyond the scope of this research. The important fact to remember is that the dimensions do change and that they change at given depths in the tank. The most important question to be asked then, is will the tank shell be capable of withstanding the

pressure at each of the various critical depths should JP-8 be introduced? Posed a different way, the question could read, are the tank shell thicknesses at each of the critical depths sufficient to withstand the additional pressure which would be introduced by JP-8 should it be used? With this latter question in mind, it is now possible to begin the analysis of the integrity of the tank structure as regards shell thickness.

As explained earlier, the more pressure is exerted at a given point in the tank, the thicker the tank shell plates or courses must be. API Manual 650 lists a very useful equation for determining the minimum allowable plate thickness (27:3-3):

$$t = \frac{(2.6)(D)(H-1)(\sigma)}{(.85)(21{,}000)}$$

where

t = minimum thickness in inches

D = the nominal diameter of the tank

H = height, in feet, from the bottom of the course under consideration to the top of the maximum fuel level

σ = the specific gravity of the liquid to be stored, but in no case less than 1.0.

Paragraph "b" below the equation states that in no case, if

the nominal tank diameter is less than fifty feet, shall the plate thickness be less than 3/16 inches.

In viewing Table 1, we see that at the maximum, the specific gravity of JP-4 is 0.801 while the maximum for JP-8 is 0.846. Both of these values are less than 1.0; thus, we must use the value of 1.0 as the specific gravity for both fuels in the plate thickness equations.

The equation itself assumes that the minimum thickness for shell plates "shall be computed from the stress on the vertical joints, using a joint efficiency factor of 0.85 [22:3-3]."

Since the only variable capable of changing in the equation when comparing JP-4 to JP-8 is that for specific gravity, the values for plate thickness for both fuels will be the same at each of the various depths to be considered. This is due to the fact that the value of 1.0 must be used for the specific gravity of both fuels. The calculation of plate thickness for the critical depths are shown below:

Table 5

Comparison of Thicknesses

Fuel Depth (ft)	Thickness (inches)	Now In Place*
28	0.157	3/16
34	0.202	.206
40	0.239	.241

*From source number 5.

At a fuel depth of 28 feet, the thickness value is actually less than 3/16 inches, but, according to API Manual 650, no plate shall have a thickness of less than 3/16 inches (22:3-3). Thus, at each point above the 28 foot fuel depth, 3/16 inch plate should be and is used.

As can be seen when comparing the values calculated using the API equation and those values for thickness possessed by the tanks, one can clearly see that the existing tank shell exceeds requirements in each case.

It may be helpful at this point to contrast the previous tank thickness values, calculated at 60°F to values calculated for a lower temperature. This is important since as the fuel becomes colder, it becomes more dense. Thus, more fuel can be placed in the same amount of volume. Since more fuel can then be placed in the tank, more pressure will be exerted by the fuel because of the additional weight. This thesis team chooses (-)20°F as the theoretical temperature to use in investigating cold weather conditions.

As far as tank shell thickness is concerned, the temperature will have no effect on calculations. This can be explained by the fact that, as mentioned earlier, the only variable in the API equation capable of changing is that for the specific gravity. At (-)20°F the values for specific gravity for JP-4 and JP-8 are 0.810 and 0.843 respectively. Thus, as required by API, the value used in

the equation for specific gravity for both fuels will be 1.0. Therefore, the values calculated previously for tank shell thickness at 60°F will not change for (-)20°F.

Since, as has been shown previously, the tank shell is sufficient to withstand the additional pressure produced by JP-8 at warm and cold temperatures, it is safe to say that no equipment or material will be required for modification of the tank in our example. Therefore, no lead time problem is involved in this portion of the analysis.

Foundation analysis. As was mentioned in the Methodology section, this thesis team will be concerned only with the critical depth when considering foundation adequacy. A detailed explanation of the critical depth is necessary before proceeding with the analysis of foundation adequacy. A definition of the critical depth can be found in Appendix A. As mentioned in a previous section, the critical depth is only a problem when it reaches a soil layer which is unsuitable to support the structure or material which is located on the surface of the soil. Soil beneath the surface is often found in stratefied layers. The consistency of the soil will almost always vary to a considerable extent in the vertical direction and to a smaller degree in the horizontal direction (20:292). An example of soil beneath the surface can be seen on the following page.

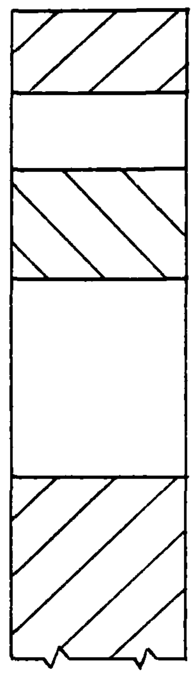


Diagram 2

Example of Soil Layers

It must also be realized by the reader that each layer of different soil material differs in its ability to support a structure or material. An unsuitable material, then, as defined by this thesis team, would be soil material which would be incapable of supporting the load which is placed upon it without the possibility of sheer failure or excessive settlement.

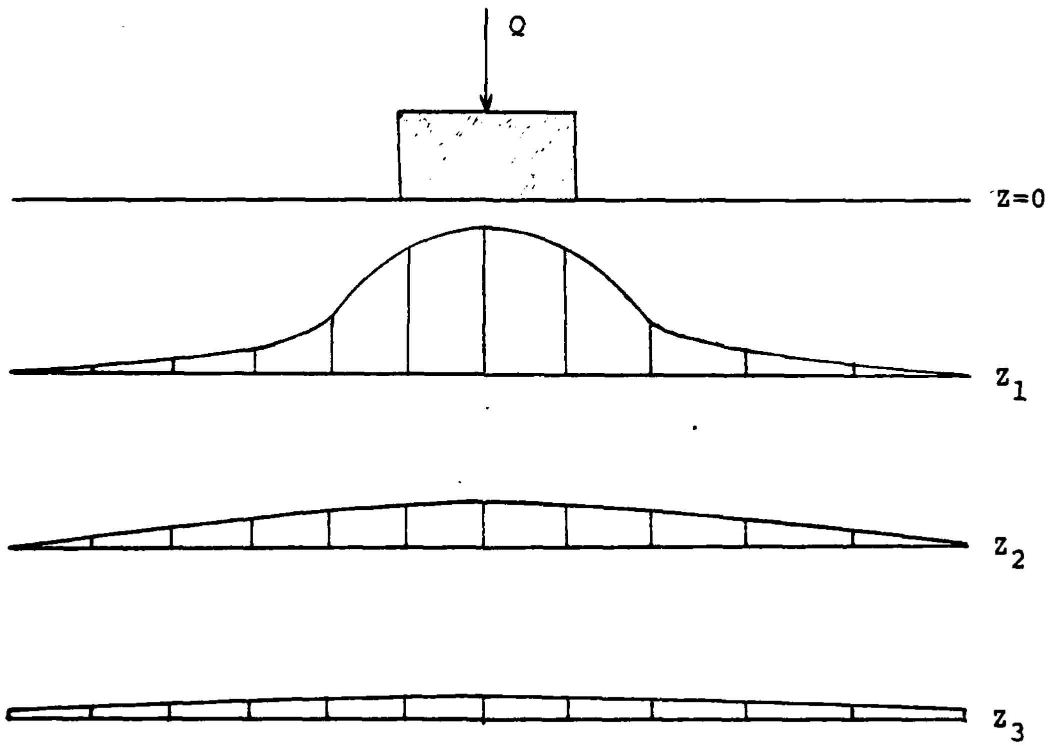
As will be proven presently, the critical depth will increase as the load applied at the surface increases. Therefore, since JP-8 is a heavier fuel, it is safe to

assume that it will increase the critical depth to some degree. It is important to know just how much of an increase will occur due to the fact that if the depth is increased enough to carry significant effects of the surface load into an area of unsuitable material, then a strengthening of the foundation will be required. A second alternative, should the increased critical depth cause a problem, would be to lower the JP-8 level in the tank to such an extent that the combined weight of fuel and storage tank would be equal to the maximum permissible level of JP-4 and its associated weight.

The example tank in this section possesses an earth foundation with a concrete ringwall. API suggests such a foundation when the ability of the natural foundation to carry shell loads directly is doubtful. The most important advantage to using a concrete ringwall, as far as this thesis team is concerned, is that such a foundation will provide a better distribution of the concentrated load of the shell which will produce a more uniform soil loading under the tank (22:B-3). This is important since the equations to be used later assume a uniform loaded condition. It is also important to remember that the ringwall itself adds nothing to the sustaining capacity of the subsoil (22:B-3). That is, it is the subsoil itself and not the concrete ringwall that supports the load of the tank and its contents.

In the analysis of the subsurface foundation conditions, this research team will employ the Westergaard and the Boussinesq formulae. From these formulae, two critical depths will be determined. The depths will differ to some degree because of the different assumptions incorporated in the equations as proposed by both men.

Both of the above mentioned formulas are based on the theory of elasticity (see Appendix A) for computing soil stresses. They represent a more accurate representation of the stress distribution beneath a surface structure (18:400). As shown in Diagram 3, the stress distribution is greatest directly beneath the applied load but continues in all directions for an infinite distance. As depth beneath the load increases, the concentration of stress directly beneath the load decreases; however, if the increases in stress were to be integrated over the entire area to which they applied, the total force would be equal to the load which is applied at the surface. It is important to remember that near the surface, the stress distribution depends on the size of the loaded area and on the contact pressure distribution. However, at depths greater than twice the width of the loaded area, the stress distribution is practiclaly independent of the way the load is applied at the surface (18:400). This is important since both the Westergaard and Boussinesq will be applied in this section



Variation of vertical stress on horizontal planes at different depths, Z.

Diagram 3

Pressure and Depth Relationship

on the assumption that the critical depth will indeed be greater than twice the width of the foundation. As will be proven later, this assumption is true.

One final assumption must be made before continuing. It is intuitively obvious that the weight or force exerted by the tank structure itself on the soil will not vary between fuel types. That is, it is a constant value. This being true, it is possible then to assume a given weight for the tank structure at least for the purpose of this research. This being the case, this thesis team will assign a weight value of two hundred tons to the tank structure. Thus, as it should be, the only variable affecting a change in the critical depth will be the variation in the fuel weight.

The Boussinesq formula was developed by Boussinesq in 1885 and adapted to soil engineering by a man named Jorgenson. The equation assumes a homogeneous, elastic, isotropic soil mass (see Appendix A) which extends infinitely in all directions beneath a level surface. In 1938, Westergaard published an analysis which improved upon the Boussinesq formula. His formula more closely represents the elastic conditions of a stratified soil mass. He assumed a "homogeneous, elastic mass which is reinforced by thin, nonyielding, horizontal sheets of negligible thickness." Both of these formulas, presented below, can be

used as presented only when the depth, Z , is greater than about twice the footing width (18:401).

Boussinesq Formula:

$$\Delta\sigma_Z = \frac{3Q}{2\pi} \frac{Z^3}{(r^2+Z^2)^{5/2}}$$

Westergaard Formula:

$$\Delta\sigma_Z = \frac{Q}{\pi_Z{}^2[1+2(r/Z)^2]^{5/2}}$$

In both cases,

$\Delta\pi_Z$ = the increase in vertical stress

Z = the depth Z (critical depth)

Q = the total applied load

r = the horizontal distance from the point of application.

The critical depth is located at a point where the vertical stress is reduced down to a point below 100 to 200 pounds per square foot. When the stress goes below this point, it can be considered negligible for all practical purposes (10). This thesis team will use 100 pounds per square foot as a criterion for insignificance simply as a safety precaution. Therefore, a value for $\Delta\sigma_Z$ of 100 will be used in both equations.

First the critical depth will be calculated using the Boussinesq formula. In order that the maximum stress can be calculated, the value for r will be zero. This will allow a calculation of stress directly beneath the applied load. The value for Q is found by adding the assumed weight of the tank structure, 200 tons, to the total weight produced by a full tank of first, JP-4, and then, JP-8. The total weight produced by each fuel can be found by multiplying the square foot area of the bottom of the tank by the pounds per square foot pressure existing at the bottom of a full tank. The latter of these values has been calculated previously and is listed in Table 4. The area of the tank bottom can be found using the equation πr^2 . Since the diameter of the example tank is 42 feet, the radius or r value in the equation is 21 feet. After installing this value in the equation and performing the mathematics, one can see that the area of ground covered by the tank bottom is 1385.44 square feet. By multiplying the square footage by the pressure per square foot, one can see that the total pressure exerted by the fuel on the soil is as follows:

Table 6

Total Fuel Pressure (60°F)

	JP-4	JP-8
Total Fuel Pressure	1,384.61 tons	1,448.62 tons

Note that the values listed were found using the highest pressure values for each fuel. This is due to the fact that this thesis team has assumed that the existing tank foundation can withstand the maximum load which can be produced by JP-4. Thus, the critical test of the foundation will involve calculations as regards the foundation's adequacy to support the maximum additional weight which can be produced by JP-8.

The value for Q which includes both tank structure weight and fuel weight is listed below:

Table 7

Total Pressure (60°F)

	JP-4	JP-8
Total Pressure (Q)	1,584.61 tons	1,648.62 tons

Now that Q has been determined, we can begin determining the critical depth for the loads related to each fuel. By solving the Boussinesq and Westergaard formulas for Z , the critical depth can be found for each of the two fuels. A tabular listing of the findings can be seen in Table 8. Thus, by either method, it can be seen that the critical depth varies by only a small margin as compared to the total depth. Due to this small increase, it is highly unlikely that the critical depth will be extended into unsuitable material.

Table 8

Critical Depth (60°F)

Method	Critical Depth (feet) JP-4	JP-8
Boussinesq	123.0	125.4
Westergaard	100.4	102.5

An analysis of the foundation at cold fuel conditions is presented below. The temperature chosen for the analysis is (-)20°F. This thesis team will use exactly the same procedure as was used for the 60°F analysis, thus, no explanation of calculations or method will be attempted unless it becomes absolutely necessary.

The specific weights will change as follows due to an increase in density: Density for JP-4 @ (-)20°F = 1.571 for JP-8 (-)20°F = 1.635.

Table 9

Specific Weights (-20°F)

Fuel	Specific Weight Lightest	Heaviest
JP-4	-	50.55
JP-8	-	52.60

The pressure associated with a full, forty foot fuel depth, tank is as follows:

Table 10

Total Fuel Pressure (-20°F)

Fuel	Pressure @ 40 Foot Depth (psf)
JP-4	2022
JP-8	2104

Now, knowing the pressure per square foot, the total pressure exerted by the fuel on the soil can be found. The total pressure for JP-4 and JP-8 is 1600.67 tons and 1657.48 tons respectively.

It is now possible to determine the critical depth for both fuels at the lower temperature. The results can be seen in Table 11 (depth calculated directly beneath the applied load).

Table 11

Critical Depth (-20°F)

Method	Critical Depth (feet) JP-4	JP-8
Boussinesq	123.60	125.80
Westergaard	100.94	102.72

As can be seen when comparing Table 11 to Table 8, the additional increase in the critical depth is minimal in every case, ranging from approximately 0.2 feet to 0.5 feet. Again, as was seen for the warmer temperature, the increase in critical depth between JP-4 and JP-8 is so minimal as to be insignificant.

From the standpoint of a critical depth analysis on the adequacy of the foundation, it has been shown that the increase in the critical depth produced by JP-8 is insignificant for warm and cold temperatures. Therefore, just as was the case for the tank shell, no material or equipment will be required to modify the foundation which exists in the thesis example. Therefore, no lead time is involved in this portion of the analysis.

Transportation

Of major concern in the analysis of the pumping system and pipe flow characteristics is the determination of the difference in energy losses caused by using JP-8 in place of JP-4. Energy is the capacity to do work. In the study of hydraulics, energy is usually expressed as head, in units of length, which is the amount of energy per pound of fluid (14:24). Analysis of the pumping system and pipe flow characteristics will be broken into two sections with the first section covering the energy loss changes in the pipe system. The second section will cover the pumping system energy changes.

Pipe system analysis. Of primary importance in the analysis of fluid flow through a pipe is the frictional head loss. Frictional head loss is actually a nonrecoverable form of heat energy caused by the interaction between the flowing fluid and the roughness of the conduit in which the fluid flows (14:25). A significant increase in head loss caused by the use of JP-8 would result in a significant decrease in the fuel flow rate and would indicate a need for facility modifications to insure that the required fuel flow rate is maintained. On the other hand, if the increase in head loss is insignificant or if there is a decrease in head loss, no facility modifications would be necessary.

In order to calculate head loss caused by friction, the Darcy Equation, as presented below, must be used:

$$H_f = f\left(\frac{L}{D}\right)\frac{V^2}{2g} \qquad (14:59)$$

where

H_f = head loss due to normal boundary friction, ft

f = a dimensionless friction factor

L = length of reach, ft

D = diameter of the pipe, ft

V = velocity of the fluid, feet per second (fps)

g = acceleration of gravity--a constant equal to 32.176 ft/s^2

There are four situations in which the Darcy equation must be used in this thesis because two fuel types are being considered (the pipe used to transport the fuel has a constant diameter) as well as two temperatures: 60°F to represent warm weather flow and -20°F to represent cold weather flow. Before the Darcy equation can be used, all but one of the above terms must be quantified. H_f is the value we seek. Before the value of f can be determined, the Reynolds number must be found. The Reynolds number is the ratio of inertial forces to viscous forces (19:225). In general, a Reynolds number below 2000 indicates that the flow is laminar while a Reynolds number exceeding 2000 indicates turbulent flow (19:256). The Reynolds number, R, may be found using the equation below:

$$R = \frac{4Q}{\upsilon \pi D} \qquad (14:71)$$

where

Q = fluid flow rate, cubic feet per second (cfs)

υ = kinematic viscosity of the fluid, square feet per second (ft^2/s)

D = pipe diameter, feet

In the case of laminar flow, f may be calculated as follows:

$$f = \frac{64}{R} \qquad (14:62)$$

If, instead, we have turbulent flow, f, the friction factor must be obtained from the Moody diagram (see Diagram 4). Knowing the Reynolds number and the relative roughness, $\frac{\varepsilon}{D}$, the friction factor can be read directly off the diagram. The relative roughness is a function of the pipe characteristics. The value ε is measured in feet and is a "representative dimension identifying the actual roughness [14:68]" of the interior surface of the pipe. The value D is the pipe diameter as measured in feet. Since these calculations are for comparison only and not for design work, the authors have assumed a one hundred (100) foot reach for all instances. The pipe diameter for each instance will be eight (8) inches since this is the pipe size used at the Wright-Patterson AFB facility. At present, using JP-4, a minimum flow, Q, of three hundred (300) gallons per minute (gpm) is maintained in the Wright-Patterson facilities (6). Using the equation $Q = AV$ (19:122), the velocity of the flow can be found. The value A represents the cross-sectional area of the pipe.

At this time, calculations for finding the frictional head loss for the first of the above-mentioned situations will be shown. It is important for the reader to understand that extra terms may appear in the calculations in the form of conversion factors used to insure uniformity of units. It should be noted that in all four situations, the highest density value possible is used to represent a "worst case"

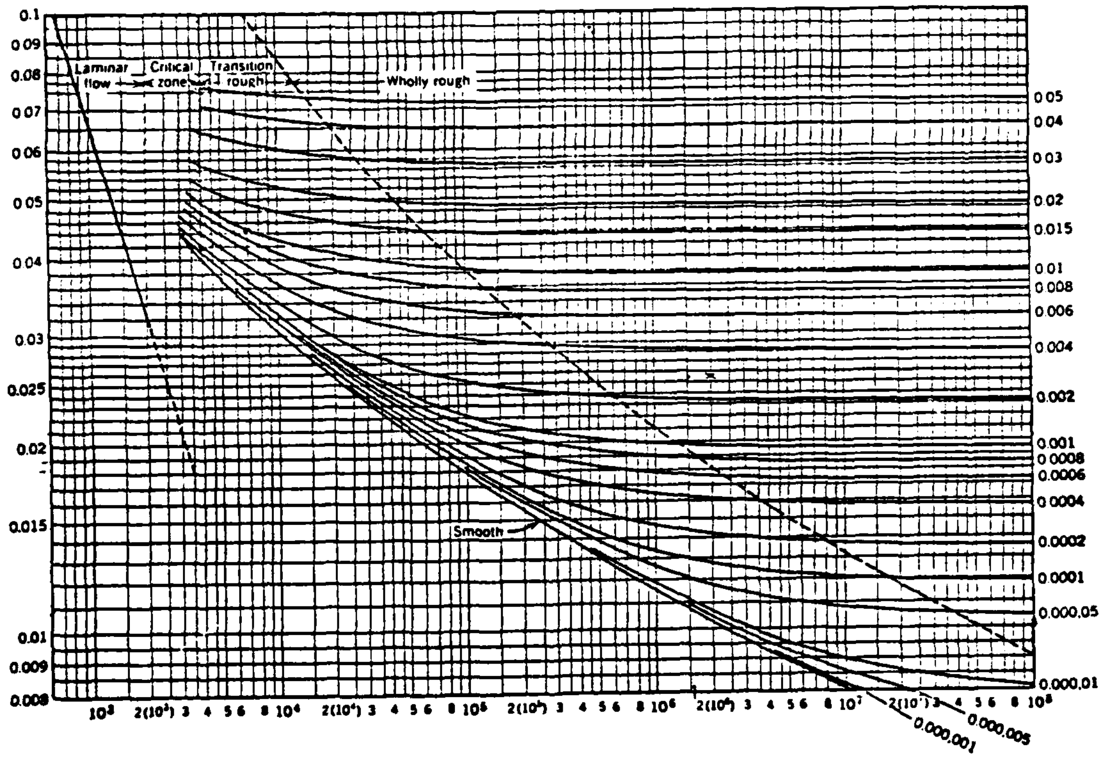


Diagram 4

Moody Diagram

approach. In other words, the authors present a range of possible densities within which the actual density of the fluid may vary due to temperature, pressure, or the quality of refinement of the product. The logic used in deciding to use the largest density value was that if the facilities can function properly with the fuel in its heaviest or most dense form, the facilities will be able to function properly in all fuel density instances.

The frictional head loss will be converted to feet_{H_2O} from $\text{feet}_{JP-4/8}$ by multiplying the latter by the appropriate specific gravity. This conversion allows comparison of the two fuels in constant terms.

<u>Situation 1</u>. JP-4 at 60°F

$Q = 300$ gpm

$L = 100$ ft

$D = 8$ inches $= .67$ ft

$g = 32.176\ \text{ft/s}^2$

$\varepsilon = .00085$ ft (1:68)

$$V = \frac{Q}{A} = \frac{\dfrac{300\ \text{gal}}{1\ \text{min}}\ \dfrac{1\ \text{min}}{60\ \text{sec}}\ \dfrac{1\ \text{ft}^3}{7.48\ \text{gal}}}{\left(\dfrac{.67\ \text{ft}}{2}\right)^2} = 1.91\ \text{fps}$$

$$Q = \frac{300\ \text{gal}}{1\ \text{min}}\ \frac{1\ \text{min}}{60\ \text{sec}}\ \frac{1\ \text{ft}^3}{7.48\ \text{gal}} = 0.67\ \text{cfs}$$

$$\frac{\varepsilon}{D} = \frac{.00085\ \text{ft}}{.67\ \text{ft}} = .00127$$

$$\upsilon = .012 \frac{cm^2}{s} \left(\frac{1 \text{ in}}{2.54 \text{ cm}}\right)^2 \left(\frac{1 \text{ ft}}{12 \text{ in}}\right)^2 = 1.292 \times 10^{-5} \text{ ft}^2/\text{s}$$

(note: 1 stoke = 1 $\frac{cm^2}{s}$)

$$R = \frac{4Q}{\upsilon \pi D} = \frac{4(.67 \text{ cfs})}{(1.292 \times 10^{-5} \text{ ft}^2/\text{s})\pi(.67 \text{ ft})} = 98548$$

f = .0235 (from Diagram 4)

$$H_L = f \frac{L}{D} \frac{V^2}{2g} = (.0235) \frac{100 \text{ ft}}{.67 \text{ ft}} \frac{1.91 \text{ fps}^2}{2(32.176 \text{ ft/s}^2)}$$

$$= 0.199 \text{ ft}_{JP-4} \text{ per 100 ft reach}$$

$$H_L = (0.199)(0.801) = 0.159 \text{ ft}_{H_2O}$$

At this time, calculations will be shown which reflect the flow of JP-8 at 60°F. In order to account for the increased density of JP-8, the authors used the mass rate of flow equation (19:122):

$$\dot{m} = \rho A V$$

where

$\dot{m}$ = mass rate of flow, slugs/sec

ρ = density, slugs/ft^3

A = pipe cross-sectioned area, ft^2

V = fluid velocity, fps

Since the mass rate of flow does not vary between use of JP-4 and JP-8, we can assume the following:

$$(\rho AV)_{JP-4} = (\rho AV)_{JP-8}$$

The cross-sectioned area will remain constant leaving the following relationship:

$$(\rho V)_{JP-4} = (\rho V)_{JP-8}$$

or,

$$V_{JP-8} = \frac{(\rho V)_{JP-4}}{\rho_{JP-8}}$$

The remainder of the calculations are similar to those of Situation 1 and thus require no explanation at this point.

Situation 2. JP-8 at 60°F

$L = 100$ ft

$D = 8$ inches $= .67$ ft

$g = 32.176$ ft/s^2

$\varepsilon = .00085$ ft

$$V_{JP-8} = \frac{(1.553 \text{ slugs/ft}^3)(1.91 \text{ fps})}{1.625 \text{ slugs/ft}^3} = 1.83 \text{ fps}$$

$$Q = AV = \pi \; \frac{.67\text{ft}}{2}^{\,2} \; (1.83 \text{ fps}) = 0.645 \text{ cfs}$$

$$\frac{\varepsilon}{D} = \frac{.00085 \text{ ft}}{.67 \text{ ft}} = .00127$$

$$\upsilon = .021 \ \frac{cm^2}{s} \ \frac{1 \ in}{2.54 \ cm}^2 \ \frac{1 \ ft}{12 \ in}^2 = 2.260 \times 10^{-5} \ ft^2/s$$

(note: 1 stoke = 1 $\frac{cm^2}{s}$)

$$R = \frac{4Q}{\upsilon\pi D} = \frac{4(.0645 \ cfs)}{(2.260 \times 10^{-5} \ ft^2/s)\pi(.67 \ ft)} = 54236$$

f = .0247 (from Diagram 4)

$$H_L = f \ \frac{L}{D} \ \frac{V^2}{2g} = (.0247) \ \frac{100 \ ft}{.67 \ ft} \ \frac{1.83 \ fps^2}{2(32.176 \ ft/s^2)}$$

$$= 0.192 \ ft_{JP-8} \text{ per 100 ft reach}$$

$$H_L = 0.161 \ ft_{H_2O}$$

Calculations will now be shown for each of the two fuel types at -20°F. These calculations are similar to those of Situations 1 and 2, respectively, with the exception that the values for the density and kinematic viscosity will change to reflect the decrease in temperature from 60°F to -20°F. The corresponding increase in density will affect the velocity of the fluid in accordance with a relationship similar to that which was derived earlier from the mass rate of flow equation:

$$V_{-20°F} = \frac{(\rho V)_{60°F}}{\rho_{-20°F}}$$

The change in the value of the fluid kinematic viscosity will affect the value of the Reynolds Number and will, in turn, cause the dimensionless friction factor to vary.

<u>Situation 3</u>. JP-4 at -20°F

$L = 100$ ft

$D = 8$ inches $= .67$ ft

$g = 32.176\ \text{ft/s}^2$

$\varepsilon = .00085$ ft

$$V_{-20°F} = \frac{(1.553\ \text{slugs/ft}^3)\ (1.91\ \text{fps})}{(1.571\ \text{slugs/ft}^3)} = 1.89\ \text{fps}$$

$$Q = AV = \pi \left(\frac{.67\ \text{ft}}{2}\right)^2 (1.89\ \text{fps}) = 0.666\ \text{cfs}$$

$$\frac{\varepsilon}{D} = \frac{.00085\ \text{ft}}{.67\ \text{ft}} = .00127$$

$$\upsilon = .024\ \frac{\text{cm}^2}{\text{s}} \left(\frac{1\ \text{in}}{2.54\ \text{cm}}\right)^2 \left(\frac{1\ \text{ft}}{12\ \text{in}}\right)^2 = 2.583 \times 10^{-5}\text{ft}^2/\text{s}$$

(note: $1\ \text{stoke} = 1\ \frac{\text{cm}^2}{\text{s}}$)

$$R = \frac{4Q}{\rho\pi D} = \frac{4(.666\ \text{cfs})}{(2.583 \times 10^{-5}\text{ft}^2/\text{s})\pi(.67\ \text{ft})} = 48999$$

$f = .0247$ (from Diagram 4)

$$H_L = f\ \frac{L}{D}\ \frac{V^2}{2g} = (.0247)\ \frac{100\ \text{ft}}{.67\ \text{ft}}\ \frac{1.89\ \text{fps}^2}{2(32.176\ \text{ft/s}^2)}$$

$$= 0.204\ \text{ft}_{JP-4} \text{ per 100 ft reach}$$

$H_L = 0.165\ ft_{H_2O}$

Situation 4. JP-8 at -20°F

$L = 100\ ft$

$D = 8\ inches = .67\ ft$

$g = 32.176\ ft/s^2$

$\varepsilon = .00085\ ft$

$$V_{-20°F} = \frac{(1.625\ slugs/ft^3)\ (1.83\ fps)}{(1.635\ slugs/ft^3)} = 1.82\ fps$$

$$Q = AV = \pi\ \frac{.67\ ft}{2}^2\ (1.82\ fps) = 0.64\ cfs$$

$$\frac{\varepsilon}{D} = \frac{.00085\ ft}{.67\ ft} = .00127$$

$$\upsilon = .075\ \frac{cm^2}{s}\ \frac{1\ in}{2.54\ cm}^2\ \frac{1\ ft}{12\ in}^2 = 8.073 \times 10^{-5} ft^2/s$$

(note: 1 stoke = 1 $\frac{cm^2}{s}$)

$$R = \frac{4Q}{\rho\pi D} = \frac{4(0.64\ cfs)}{(8.073 \times 10^{-5} ft^2/s)\pi(.67\ ft)} = 15065$$

f = .0305 (from Diagram 4)

$$H_L = f\ \frac{L}{D}\ \frac{V^2}{2g} = (.0305)\ \frac{100\ ft}{.67\ ft}\ \frac{1.82\ fps^2}{2(32.176\ ft/s^2)}$$

$= 0.234\ ft_{JP-8}$ per 100 ft reach

$H_L = 0.197\ ft_{H_2O}$

By comparing the frictional head losses, it is evident that the difference in head loss from JP-4 to JP-8 at both of the temperatures is quite small and insignificant. As will be discussed in Chapter IV, this leads the authors to the conclusion that no modifications to presently operational piping systems will be necessary.

If a pipe system were used with other than an eight inch diameter, assuming that the flow rate (Q) does not change from the three hundred gallons per minute discussed earlier, the problem would deviate slightly from that which was presented. In the case of the use of a larger diameter pipe, the fluid velocity (V) would decrease due to the larger cross-sectional area of the pipe. This is based on the flow equation, $Q = AV$. The relative roughness $\frac{\varepsilon}{D}$ of the pipe would decrease, again due to the larger pipe size. The Reynolds Number would also decrease as the pipe diameter increased. For example, using values for JP-4 flowing through a twelve inch diameter pipe in 60°F weather, we would experience a Reynolds Number of approximately 66,000 which is well within the turbulent flow range. Using the Moody diagram (Diagram 4), a friction factor of about 0.0220 would be obtained. Therefore, the frictional head loss per one hundred foot reach would be approximately 0.0247 ft_{JP-4}. Use of a six inch diameter pipe would result in a frictional head loss of approximately 0.8816 ft_{JP-4}. It can be seen that the frictional head loss varies as the

diameter of the pipe is changed and, therefore, it is suggested that this head loss be calculated to suit the reader's needs in accordance with the particular pipe size with which he is concerned.

Pump system analysis. Of primary concern in the analysis of a pump system used to transport a fluid is the amount of energy required to force the fluid to flow at, or in excess of, a minimum required flow rate. Some energy may be supplied by a pressure head as a result of the fluid having some height or elevation, at the upstream end of the pipe system, above the height of the fluid discharge point. The remainder of the energy must be supplied by a pump or pump system. This energy is represented by the symbol E_p in Bernoulli's equation, as discussed below.

If this analysis shows that there is a significant difference in the energy required to pump JP-8 as opposed to JP-4, further analysis will be required to determine if the present pumps will be adequate to supply the needed energy. If the present pumps are found to not be adequate, the authors will conclude that modifications of the pumping system are necessary. If, on the other hand, it is found that the pumps are adequate to provide the additional energy or that there is, indeed, no significant difference in the energy required to pump JP-8 as opposed to JP-4, the authors

will conclude that no modifications to the present pumping system are necessary.

In this analysis of the pumping system, the most important factor to consider is the required increase in head, as produced by the pump system, to maintain the minimum fuel flow rate of three hundred (300) gpm. To avoid unnecessary repetitious calculations, the authors have analyzed the pumping system using a hypothetical system. This system is designed as a "worst" case system in that the level of fluid in the tank is assumed to be virtually zero so that the corresponding head ($\frac{P_1}{\gamma}$) does not help to force the fluid through the pipe. Therefore, the value for Z_1 is zero (0). As with the analysis of the fuel flow in the pipe network, four situations will be presented here corresponding to the analysis of each of the two fuel types of both 60°F and -20°F. In this analysis, the authors will use the Bernoulli Equation:

$$\frac{P_1}{\gamma} + \alpha\frac{V_1^2}{2g} + Z_1 + E_p = \frac{P_2}{\gamma} + \alpha\frac{V_2^2}{2g} + Z_2 + H_f + H_m \quad (19{:}142)$$

where

P = gage pressure at points 1 and 2 , respectively, lbs/ft^2

γ = specific weight of the fluid, lbs/ft^3

α = dimensionless kinetic energy correction factor

V = fluid velocity at points 1 and 2 , respectively, fps

Z = height of the fluid above a predetermined datum at points 1 and 2 , respectively, ft

E_p = head added to the flow by the pump between points 1 and 2 , ft

H_f = frictional head loss, ft

H_m = minor head losses, ft

(refer to Diagram 5).

For the purpose of this analysis, the values for both P_1 and P_2 will be zero (0) lbs/ft^2 due to the fact that both locations are vented to the atmosphere. The value for V_1 will also be zero (0) fps since the surface of the fluid moves so slowly when compared to the velocity of the flow in the pipe system. The value for α is normally assumed to equal one (1) for turbulent flow and two (2) for laminar flow (2:141). As before, g is a constant with a value of 32.176 ft/s^2. The value of E_p is that which is sought. The velocity of the flow exiting the pipe system at point 2 is represented by V_2. Z_2 was chosen by the authors to represent the elevation datum and thus has a value of zero (0) feet. When multiplied by the length of pipe (measured in hundreds of feet) through which the fluid flows, the frictional head loss, calculated in the analysis of pipe flow, may be used for H_f.

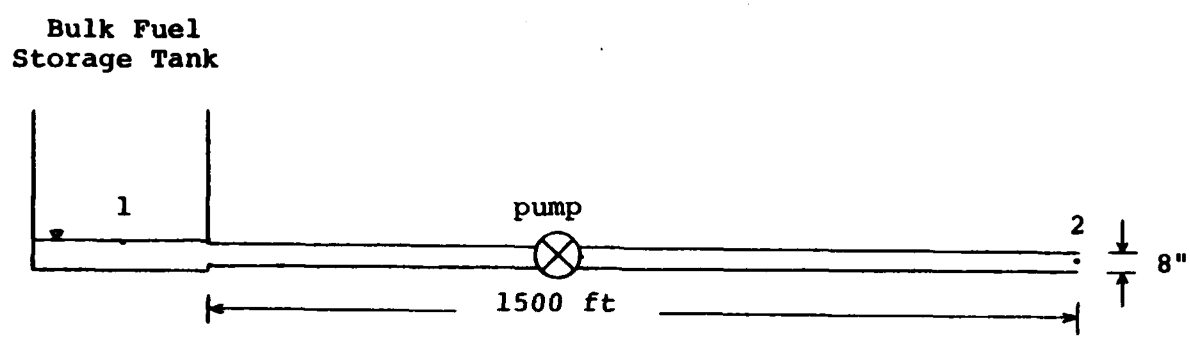


Diagram 5

A Typical Piping System
(not to scale)

At this time, calculations for analyzing the pump system energy will be shown. The energy provided by the pump is converted to feet of water by multiplying the head (in feet of JP-4/8) by the specific gravity of the fuel.

Situation 1. JP-4 at 60°F

$D = 8 \text{ inches} = .67 \text{ ft}$

$A = \pi r^2 = \pi \frac{.67}{2}^2 = 0.3491 \text{ ft}^2$

$Q = 300 \text{ gpm}$

$$V = \frac{Q}{A} = \frac{\frac{300 \text{ gal}}{1 \text{ min}} \; \frac{1 \text{ min}}{60 \text{ sec}} \; \frac{1 \text{ ft}^3}{7.48 \text{ gal}}}{0.3491 \text{ ft}^2} = 1.913 \text{ fps}$$

$L = 1500 \text{ ft}$

$H_f = 0.199 \text{ ft}_{JP-4}$ per 100 ft of reach

(minor losses neglected)

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 + E_p = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 + H_f$$

$P_1 = 0$

$V_1 = 0$

$Z_1 = 0$

$P_2 = 0$

$Z_2 = 0$

thus,

$$E_p = \frac{1.913 \text{ fps}^2}{2(32.176 \text{ ft/sec}^2)} + 15 \text{ (.199 ft/100 ft)}$$

$$E_p = 3.042 \text{ ft}_{JP-4}$$

or

$$E_p = (3.042 \text{ ft}_{JP-4})(0.801) = 2.437 \text{ ft}_{H_2O}$$

Calculations for the next three Situations follow the same format as Situation 1 and are therefore self-explanatory. All Situations are subject to the same assumptions.

<u>Situation 2</u>. JP-8 at 60°F

$D = .67$ ft

$A = 0.3491 \text{ ft}^2$

$Q = 300$ gpm

$$V_2 = \frac{\rho_1 V_1}{\rho_2} = \frac{(1.553)(1.913)}{1.625} = 1.828 \text{ fps}$$

$L = 1500$ ft

$H_f = 0.192 \text{ ft}_{JP-8}$ per 100 ft of reach

(minor losses neglected)

$$E_p = \frac{V_2^{\,2}}{2g} + H_f$$

$$E_p = \frac{1.828 \text{ fps}^2}{2(32.176 \text{ ft/s}^2)} + 15\ (.192) = 2.932 \text{ ft}_{JP-8}$$

$$= 2.457 \text{ ft}_{H_2O}$$

Situation 3. JP-4 at -20°F

$D = 0.67$ ft

$A = 0.3491$ ft^2

$Q = 300$ gpm

$$V_2 = \frac{\rho_1 V_1}{\rho_2} = \frac{(1.553)(1.913)}{1.571} = 1.891 \text{ fps}$$

$L = 1500$ ft

$H_f = 0.204$ ft$_{JP-4}$ per 100 ft of reach

(minor losses neglected)

$$E_p = \frac{V_2^2}{2g} + H_f$$

$$E_p = \frac{(1.891)^2}{2(32.176)} + 15\ (.204) = 3.116 \text{ ft}_{JP-4}$$

$$= 2.524 \text{ ft}_{H_2O}$$

Situation 4. JP-8 at -20°F

$D = 0.67$ ft

$A = 0.3491$ ft^2

$Q = 300$ gpm

$$V_2 = \frac{\rho_1 V_1}{\rho_2} = \frac{(1.828)(1.625)}{1.635} = 1.817 \text{ fps}$$

$L = 1500$ ft

$H_f = 0.234$ ft$_{JP-8}$ per 100 ft of reach

(minor losses neglected)

$$E_p = \frac{V_2^{\,2}}{2g} + H_f$$

$$E_p = \frac{(1.817)^2}{2(32.176)} + 15\ (.234) = 3.561\ ft_{JP-8}$$

$$= 3.002\ ft_{H_2O}$$

A comparison of the values for the energy required of the pumps show that no significant difference exists between the energy required to pump JP-4 and that required to pump JP-8. This holds for both warm and cold weather flow. This leads the authors to conclude that, as with the piping system, no modifications to the current pumping system will be necessary. Chapter 4 contains a full discussion of this conclusion.

Chapter 4

CONCLUSIONS AND RECOMMENDATIONS

Conclusions drawn from, and recommendations made on, the analysis presented in Chapter 3 is the subject of this chapter. First, in-depth conclusions will be drawn in accordance with the Research Objectives, the Research Questions, and the analysis presented in Chapter 3. The conclusions will be presented in two separate sections, the first dealing with the storage facilities and the second dealing with the transportation facilities. Next, recommendations for future study will be made by the authors and will be presented as a singular unit. The recommendations section will serve to provoke interest and research in areas related to but not covered in this thesis effort.

Storage

Hydrostatic effect. Based on the analysis portion of Chapter 3 regarding the hydrostatic effect, this thesis team must conclude that no modification need be made to the tank shell should a conversion to JP-8 be made. The analysis is further substantiated by Mr. Frank Morse of the Air Force POL Technical Assistance Team. Mr. Morse concurs with the findings of this thesis as regards tank shell thickness

sufficiency (15). In a letter dated 8 May 1980, Mr. Morse stated that no modification need be made in this area.

Further study in this area may well direct itself towards an analysis of various other regions of the tank which may be affected by hydrostatic pressure. These other regions include such items of design as the bottom plates, the vertical and horizontal joints and bolted door sheets to mention a few. A study of these items should include an analysis of hydrostatic pressure at each level of interest and the capacity of the above listed items to withstand the additional pressure produced by JP-8 at the various levels.

Foundation analysis. This thesis team concludes that no modification of the existing foundation is required based on the analysis findings regarding the critical depth in the foundation section of Chapter 3. Although the critical depth does increase, this increase is considered to be insignificant because of its magnitude. When considering this last sentence, one must keep in mind that the science of soil mechanics does have its limitations. Perhaps the greatest limiting effect arises from the assumption that soil is an idealized homogeneous material. This assumption is made in most areas of soil mechanics including that area utilized in this analysis. Of course, soil is not a homogeneous material and any analysis will vary in its accuracy according to just how close to a homogeneous material the soil is (10).

These last few statements should have convinced the reader that soil mechanics is not as exact a science as many would like. Still, it is the best science available and has been proven to be remarkably accurate (10). Then, with a grasp on the limitations of soil mechanics, one can realize that a difference in critical depth of only two feet is indeed insignificant. As in the previous section, Mr. Frank Morse, the lead engineer of the Air Force POL Technical Assistance Team, again concurs with the findings presented in this thesis (15).

The recommendations for further study in this section are virtually limitless but have been narrowed to those listed below. These recommendations are limited to the area of subsurface analysis. Two areas in particular can be given extremely detailed consideration. The first of these areas is the shear strength of each layer of soil beneath the tank structure within range of the critical depth. The second area involves a study of the settlement characteristics of each layer of soil within range of the critical depth. The most practical approach to an analysis of the above mentioned areas would involve the use of shear and settlement tests in a soils laboratory. Of course, in order to perform such tests, soil borings must be taken to a level at least as deep as the critical depth so that soil samples can be gained from each affected soil layer.

Transportation

In this section, the conclusions drawn from the analysis of the transportation facilities will be discussed. This section will be divided into two parts. The first part will cover the discussion of the conclusions drawn from the analysis of the frictional head loss which occurs in the piping system, as presented in Chapter 3. The second part of this section will cover the conclusions drawn from the analysis of the energy required of the pumping system, also as presented in Chapter 3.

Pipe system analysis. Upon close examination of the frictional head losses, as calculated in Chapter 3, for warm weather flow of both JP-4 and JP-8, the reader can see that the actual difference between the two is very small. Calculations reveal that there is only a 1.3% increase in the frictional head loss, as measured in feet_{H_2O}, of JP-8 as compared to the head loss associated with JP-4. This, in itself, is a very insignificant increase in head loss. The insignificance of the increase is magnified by the fact that the head loss due to friction is so small to begin with. When looking at the two fuels in cold weather conditions we see that there is a 19.4% increase in frictional head loss associated with the use of JP-8 as opposed to the use of JP-4. While this is a seemingly large change in head loss, the reader is reminded to keep in mind the magnitude of the

actual values of the head losses. In the case of cold weather flow of JP-4, the head loss per one hundred feet of reach is 0.165 ft_{H_2O} and that of JP-8 is 0.197 ft_{H_2O}. The head loss of JP-4 (0.165 ft_{H_2O}) converts, roughly, to two inches of head loss which is quite insignificant. The authors are, therefore, led to conclude that no modifications of the present piping system are necessary. These conclusions do not necessarily apply when analyzing a pipe system with a diameter other than eight inches.

Pump system analysis. At this time, the authors will discuss their conclusions concerning the analysis of the pumping system as presented in Chapter 3. As was the case in the analysis of the piping system, the reader can see that there is only a very insignificant difference between the energy required to pump JP-8 under warm weather conditions as opposed to the energy required to pump JP-4 under similar conditions. In fact, when comparing the appropriate values as measured in $feet_{H_2O}$, it can be seen that there is only a 0.8% increase in energy required to pump JP-8 instead of JP-4. Not only is this increase in required energy small, but so are the actual energy values. For example, warm weather flow of JP-4 required energy amounting to only 2.437 ft_{H_2O} which is, in itself, a small load for a pump installed in such a fuel storage and transportation facility. While the increase in energy required for cold weather flow

of JP-8, compared to that of JP-4, is 18.9%, the reader must, as discussed before, take into consideration the magnitude of the actual values. For instance, cold weather flow of JP-4 requires approximately 2.524 ft_{H_2O} of energy while flow of JP-8, under similar conditions, requires 3.002 ft_{H_2O}. As stated above, these loads are quite insignificant compared to the capacity of a pump installed for such a purpose as pumping large quantities of fuel. The authors, therefore, conclude that no modifications, or construction, to the present pumping facilities will be necessary.

The conclusions drawn by the authors are substantiated by Mr. Frank Morse, the lead engineer of the Air Force POL Technical Assistance Team at Kelly AFB, Texas. In a letter to this thesis team, dated 8 May 1980, Mr. Morse explained that no modifications would be necessary to existing facilities (15). These conclusions eliminate the need for concern about construction of new facilities, or modifications to the present facilities, and the lead time associated with the acquisition of the materials necessary for such construction. These conclusions also eliminate the need for concern about the management of fuel disbursement during the construction process as well as the training of personnel to operate and maintain the new facilities. While these are only a sampling of the areas that would normally be affected by the need for modifications of the facilities, the list is by no means complete and is offered for the sole

purpose of giving the reader some idea of what the magnitude of the problem would have been like had the modifications been necessary.

Further Recommendations

The authors recommend several areas related to this thesis effort which may be studied in the future. Included are studies concerning the analysis of underground type fuel storage tanks. These tanks, unlike those studied in this thesis, are located below ground level and, therefore, may possess unique problems as regards fuel conversion, not only in the storage area but also in the area of pipes and pumps. Another area of interest involves fire safety. A detailed analysis of the possible safety advantages to be gained by converting to JP-8 would make for an interesting topic of study. It is suggested that this study revolve around the use of JP-8 in facilities discussed in this thesis.

Finally, a study could be conducted to cover the possible design of a more efficient pump system for the sake of conserving some of the energy required to operate them. This study could be expanded to include a study of the relationship between the height of fluid in the bulk storage tank and the energy required to maintain the minimum flow rate in the pipe system. This may involve a determination of the feasibility of replacing the current pump system with a series of valves or less energy consuming pumps.

APPENDIX A

OPERATIONAL DEFINITIONS

Aircraft turbine fuel is the fuel used in aircraft powered by turbine or jet engines. One such fuel is JP-4 which is a naptha-based turbine fuel currently used by the USAF in its aircraft. It contains rust and ice inhibitors. The other turbine fuels available today are kerosene-based. These fuels include Jet-A, Jet A-1, JP-5, and JP-8. The latter two of these fuels contain corrosion and ice inhibitors whereas the first two do not since they are used almost exclusively in the commercial air industry.

The above mentioned fuels possess certain qualities. First, the flash point is the lowest temperature at which the vapor of a combustible liquid can be made to ignite momentarily in air. The flash point of JP-8, for example, is much higher than that of JP-4 causing cold start and air relight problems. Second, volatility is the quality of evaporating readily at normal temperatures and pressures. JP-4 is a much more volatile fuel than is JP-8. Third, viscosity is the degree to which a fluid resists flow under an applied force. Conversion to JP-8 introduces a viscosity problem in that as operating temperatures approach (-)20°F, JP-8 becomes very viscous causing pumps and filters to be strained more than normal. The problem is compounded greatly as JP-8 approaches (-)58°F, its freezing temperature. Another fuel property which should be mentioned is

vapor pressure. This is the pressure which is exerted on an environment by a vapor in equilibrium with a solid or a liquid at a specified temperature.

One of the most outstanding physical problems associated with aircraft use of JP-8 is air relight. Air relight involves reignition of the engine while the aircraft is in flight. On occasion, aircraft turbine engines have been known to "flame out," an event marked by a loss of ignition of the fuel resulting in a loss of thrust. It is at this point that air relight is required.

When dealing with the bulk storage facilities used to store the turbine fuel hydrostatic pressure must be taken into account. Hydrostatic pressure is that pressure which is exerted by a static liquid on its environment by virtue of its depth.

A key ingredient in the production of JP-4 turbine fuel is naptha. Naptha is defined as "any of various volatile often flammable liquid hydrocarbon mixtures used chiefly as solvents and dilutents and as raw materials for conversion to gasoline [23:1502]."

Soil possesses several characteristics, one of which is shear strength. This is the ability of the soil to resist sliding along internal surfaces within its mass. Shear failure then is an occurrence marked by the sliding of these internal surfaces. The critical depth of a soil is that depth at which the pressure exerted by a structure or

material on the surface of the soil is negligible (usually 100-200 lbs/square foot) (10). Excessive settlement of a structure can be considered to be any amount of settlement incurred which disrupts the normal operating ability or structural integrity of a facility or structure.

The storage tank used as an example in Chapter 3 is constructed of courses which are butt-welded together. A course is simply a series of sheets of steel plate located at the same elevation around the tank. Stated simply, these courses can be said to be stacked one on another until the required tank height is reached. The term "butt-welded" refers to the way in which the courses are joined. Butt-welded simply means that the plates of each course were stacked end to end with no overlapping allowed.

There exist some characteristics and theory about soil itself which need defining. A homogeneous soil is a soil which is consistent throughout its mass. That is, it is not stratefied into layers which possess different characteristics. An isotropic soil is one which exhibits equal tendency for compressibility in all directions. When one assumes that a soil is elastic, he is saying that it is capable of recovering its original size and shape after deformation.

The theory of elasticity refers to any soils theory which assumes that the relationship between stress and strain can be defined mathematically.

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